CRREL Report 98-8

US Army Corps of Engineers®
Cold Regions Research & Engineering Laboratory

Remediation of Wastewater by Land Treatment

Consideration of Soil Temperatures in Winter

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August 1998

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

Abstract: The impact of the winter environment on land treatment of wastewater has been investigated in terms of predicted winter-long soil temperature histories and depths of frost penetration that were obtained from numerical modeling of heat transfer and phase change in sandy soil. Severity of the winter, soil porosity, and soil moisture content are varied to determine the depth-dependent changes in soil temperature that result. The impact of wintertime soil temperatures on nitrification and denitrification is presented in terms of thickness and persistence of a soil layer cold enough to severely inhibit microbial activity. The model WASTEN is used to predict concentrations of ammonium and nitrate in soil at the end of a remediation cycle. Rates of nitrification and denitrification are varied to be consistent with decreasing microbial activity as soil cools. Depending on soil temperature and thickness of the cold soil layer, peak concentrations of ammonium and nitrate remaining in the soil can be as much as 40–100% greater than under warm soil conditions.

Cover: *Predicted durations of soil temperatures inhospitable to nitrifying and denitrifying bacteria. Periods when soil at a given depth is colder than 5°C are indicated with horizontal lines. Soil temperatures were predicted by numerical simulations for a sandy soil of 20 wt. % moisture content and 0.47 porosity under four winter conditions.*

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PREFACE

This report was prepared by Dr. Lindamae Peck, Geophysicist, Geophysical Sciences Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire. Funding for this project was provided by the Army Environmental Quality Research Program, work unit AF25-RT-005, *Investigation of the Feasibility of Low-Temperature Biotreatment of Hazardous Wastes*, and work unit AF25-ET-510, *Biotreatment of Explosives/Organics in Cold Regions*.

The author thanks Daniel Leggett, Louise V. Parker, and Dr. Charles M. Reynolds, CRREL, for their technical reviews of this manuscript.

CONTENTS

ILLUSTRATIONS

Figure

TABLES

Table

Remediation of Wastewater by Land Treatment
Consideration of Soil Temperatures in Winter

LINDAMAE PECK

INTRODUCTION

Numerical simulations of heat transfer and phase change in soil under a range of winter conditions were done to investigate the potential impact of cold regions conditions on treatment of nitrogen (N) in wastewater by land application. The specific remediation processes considered were nitrification and denitrification, by which ammonium nitrogen is oxidized to nitrate and nitrate in turn is converted to gaseous nitrogen. Because the microbial and enzymatic activities responsible for nitrification and denitrification decrease and eventually cease at progressively lower temperatures, the efficacy of land treatment of wastewater is reduced during winter. The magnitude of the adverse impact of winter on remediation depends on the temperature of the soil and the duration of soil temperatures inhospitable to microorganisms.

Examples of predicted reduced effectiveness of land treatment in winter were obtained from WASTEN, which models nitrogen transport and transformations in soil under scenarios representative of wastewater applications.

BACKGROUND

Disposal of municipal wastewater on land raises the possibility of polluting groundwater through the addition of chemicals that leach to the water table. An example is nitrogen. Ammonium nitrogen ($NH_4^+ - N$) and nitrate ($NO_3^- - N$) are introduced to soil directly in typical municipal wastewater; other nitrogen compounds subsequently form in the soil as ammonium is biochemically altered. In aerobic soils, $NO_3^- - N$ is a dominant, final species of N. Nitrate is readily leached from vadose zones into groundwater. Nitrate leaching has deleterious consequences, including reduced potability of water supplies and unwanted growth of aquatic plants (algal blooms) in surface receiving waters.

Managed wastewater treatment by land application exploits natural ways of lessening the amounts of deleterious forms of nitrogen before they enter groundwater. Nitrification is the process by which microorganisms in soil oxidize ammonium to nitrite. Nitrite is subsequently oxidized to nitrate (Fig. 1). Nitrification makes avail-

Nitrification

$$\underset{\text{(ammonium)}}{NH_4^+} + 1.5\ O_{2(aq)} \rightarrow \underset{\text{(nitrite)}}{NO_2^-} + H_2O + 2H^+$$

a. Oxidation of ammonium to nitrite.

$$NO_2^- + 0.5\ O_{2(aq)} \rightarrow NO_3^-\ O_{2 \mp aq^-} \rightarrow \underset{\text{(nitrate)}}{NO_3^-}$$

b. Oxidation of nitrite to nitrate.

Denitrification

$$NO_3^- + \underset{\text{(carbohydrate)}}{1.25\ [HCHO]} \rightarrow \underset{\text{(nitrogen gas)}}{0.5\ N_2} + 0.75\ H_2O + 1.25\ CO_2 + OH^-$$

or

$$NO_3^- + [HCHO] \rightarrow \underset{\text{(nitrous oxide)}}{0.5\ N_2O} + 0.5\ H_2O + CO_2 + OH^-$$

Figure 1. Nitrification and denitrification reactions. (After Delwiche 1981.)

able a major nitrogen source (nitrate) assimilated by higher plants, and also removes a detrimental form of nitrogen (ammonium). Denitrification is the reduction of nitrate to gaseous nitrogen, nitrogen oxides. These gases are then lost from the soil via volatilization. Water quality following overland flow treatment shows seasonal differences, with the concentration of ammonium nitrate in the runoff increasing as soil cools from 17°C to 0°C (Martel et al. 1980).

WASTEN was created as a research tool for the investigation of nitrogen transport and transformations in soil (Selim and Iskandar 1980). It is used as a management tool for designing land treatment of wastewater: the concentrations of applied ammonium and nitrate, the amount and duration of wastewater application, and the application cycle are specified, and nitrogen removal by nitrification, denitrification, and plant uptake as the wastewater percolates through the soil is predicted. The model considers relevant aspects of the soil, such as layering, layer-specific hydrology, and nitrogen transformation values; initial distributions of water and nitrogen species in the soil profile; plant root distribution and growth in the soil; rate of nitrogen uptake by plants; and evapotranspiration. This is accomplished through the interaction of two submodels, one for nitrogen and one for water. The former describes the transport and transformation of nitrogen species in the soil and also nitrogen uptake by plants. The latter describes water infiltration, water movement in the soil column, and uptake of water by plants.

FACTORS INFLUENCING NITRIFICATION AND DENITRIFICATION

The major soil factors are temperature, pH, moisture, and oxygen content (aeration), but only temperature is considered directly here. Soil pH and oxygen content are assumed to be suitable for the occurrence of nitrification and denitrification, such that they do not limit the rates at which nitrification and denitrification proceed. Soil moisture is considered indirectly through its influence on thermal properties of the soil, which in turn alter the predicted soil temperature profiles. The heat transfer simulations are conducted for soil with a moisture content of 10, 20, or 30 wt. %. The moisture content is the same throughout the soil column and does not change during a winter-long simulation. For the WASTEN simulations, initial soil moisture varies with depth and changes as the wastewater percolates through the soil.

Cold effects

The temperature range for denitrification is 3–85°C (Nömmik 1956), with an optimum at 65°C; this range is larger than for nitrification (2–35°C, Frederick 1956) because there is greater species diversity among the denitrifiers (Jacobson and Alexander 1979). At the lower end of the temperature range, however, the rates at which nitrification and denitrification proceed are greatly reduced. In experiments with Charlton loam (pH 6.3) and Windsor sandy loam (pH 5.5), Jacobson and Alexander (1979, 1980) found that denitrification occurred slowly at 7°C, but not at all, i.e., at an immeasurable rate, in 1°C soil, as indicated by the fact that there had been no nitrate loss in the colder soil at the end of seven days. For Charlton loam treated with glucose (500 ppm C) as a carbon source, the doubling time for populations of denitrifying bacteria increased by a factor of four as the loam was cooled, from 13 hours at 21–22°C to 50 hours at 7°C. The doubling time for denitrifying bacteria in glucose-treated Windsor sandy loam also increased by a factor of four as the soil temperature changed, from 10 hours at 21–22°C to 42 hours at 7°C. In a subsequent study (Parker et al. 1981), maximum rates of nitrification (kg N/ha per day) for Windsor soil decreased from 2.8 at 23°C to 1.6 at 5°C, a factor of ~2, and those for Charlton soil decreased from 2.2 to 0.3, a factor of ~7.

Other low-temperature studies (e.g., Anderson and Boswell 1964, Bailey 1976, Keeney et al. 1979, Azevedo et al. 1995) confirm that the efficacy of denitrification and nitrification processes is severely reduced at temperatures of 10°C or lower. This reflects the temperature dependence of the organisms that oxidize ammonium and nitrite, as summarized in Leggett and Iskandar (1980). It is possible to moderate the inhibiting effect of cold, however, by selecting bacteria that have low optimum temperatures. For instance, Halmo and Eimhjellen (1981) created two denitrifying sludges, one with bacteria having an optimum growth temperature of 5°C (low-temperature sludge) and one with bacteria having an optimum growth temperature of 20°C (high-temperature sludge). Denitrification in both sludges proceeded at slower rates as the temperature was lowered from 20 to 5°C, but the reduction in rate was only a factor of 2 for the low-temperature sludge, while it was a factor of 4–5 for the high-temperature sludge.

Relevant soil depths

Nitrifying bacteria are most numerous in surface soils at depths of 0 to 10 cm (Ardakani et al. 1974). As summarized in Focht and Verstrate (1977), this is attributed to near-surface soil having the highest levels of organic matter, of total nitrogen, and of O_2, and also the highest cation exchange capacity (Brady 1974). The latter attribute causes ammonium to be retained in the upper portion of soil for use by the bacteria.

Microbial activity on nitrogen species can, however, occur deeper in soil, as shown by Cho et al. (1979), who studied denitrification intensity as a function of depth in three loams. They expressed their results as equations for the dependence of denitrification intensity on temperature and on depth (exponential decrease with depth over the range 0 to 150 cm). By incorporating a relationship for soil temperature as a function of depth and time of year, Cho et al. devised equations to predict the seasonal fluctuation in the depth at which peak microbial activity occurs, assuming that denitrification is not rate limited by some other factor, such as availability of carbon. Because soil at depth during winter in seasonally cold regions is warmer than surface soil, denitrification can continue at depth even when a surface layer of soil is colder than the threshold temperature for microbial activity. The history of denitrification in a soil column potentially is one of year-round denitrification in soil below the frost line, with seasonally dependent denitrification intensity (high in summer, zero in winter) in the surface layer of soil that freezes in winter.

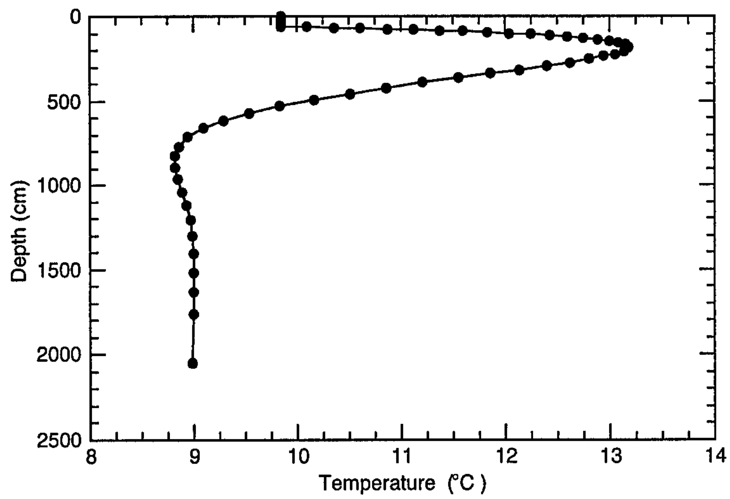


Figure 2. Initial temperature condition for the numerical simulations.

NUMERICAL MODELING TO PREDICT SOIL TEMPERATURES UNDER REPRESENTATIVE WINTER CONDITIONS

Heat transfer model

A one-dimensional version of the model XYFREZ (O'Neill 1987) is used to simulate heat transfer in the soil. The program uses finite elements in space and finite differences in time to model heat conduction. Latent heat effects due to a phase change in water within the soil are included through a singularity in the heat capacity of the soil (Peck and O'Neill 1997). The moisture content of the soil remains unchanged throughout a given simulation. Neither moisture diffusion due to a temperature gradient in the soil, nor an influx of water, as from melting snow or a surface application of wastewater, is considered.

Initial soil temperatures

The one-dimensional finite element mesh was initialized with the temperatures plotted in Figure 2. This temperature profile was established during a previous study (Peck and O'Neill 1995), as follows. Temperatures measured at 60-cm depth in a sandy loam soil at a South Royalton, Vermont, field site during a full year were converted to a daily average. That temperature history then drove the heat transfer calculations over a one-year time span. This was repeated for a 20-year time period, assuming a uniform initial temperature approximately equal to the yearly average at 60 cm and assuming that the temperature profile at a depth of ~20 m remains flat. By the end of the simulation a stable yearly pattern of temperature profiles for soil depths of 0.6 to 20 m had become established (Fig. 3), as well as a stable temperature value at depth.

The final temperature profile used to initialize the finite element mesh consists of the simulated profile for day 300 (27 October) from Figure 3 for the depth range 0.6 to 20 m spliced to a constant temperature profile from 0.6 m to the surface. The flat, near-surface profile is a computational convenience that disappeared quickly and did not significantly affect the results.

Boundary conditions

Four boundary conditions for the temperature of the soil surface (0 cm) were used to investigate the dependence of soil temperature on the relative severity of the winter (Fig. 4). The first boundary condition, BC-Warm, is derived from soil surface temperature data at the South Royal-

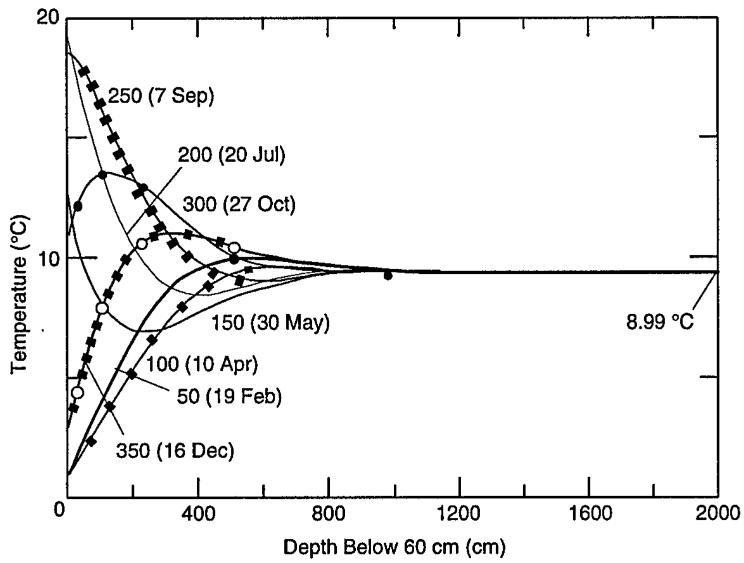


Figure 3. Calculated soil temperature profiles for depths of 0.6 to 20 m on selected days (day 1 is 1 January). The temperature profiles were obtained from numerical simulations of heat flow at depth during a 20-year period based on measured soil temperatures at a depth of 0.6 m.

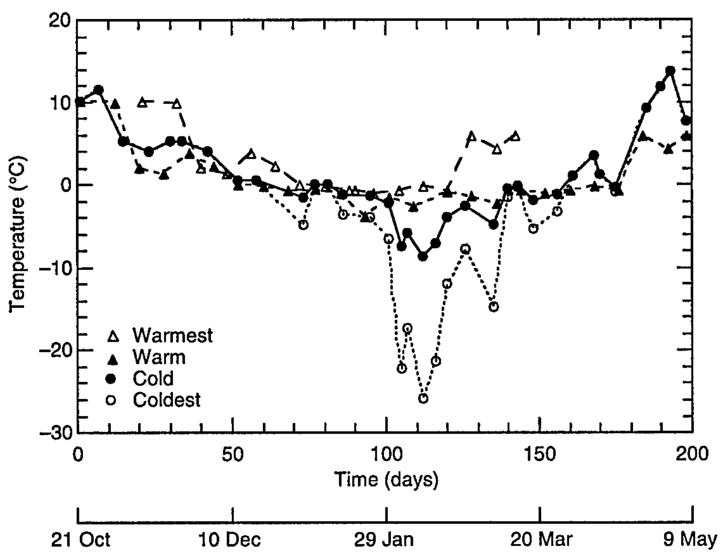


Figure 4. Soil surface temperatures corresponding to BC-Coldest, BC-Cold, BC-Warm, and BC-Warmest.

ton site for 22 October 1991 to 6 May 1992. This produced a soil surface temperature history that has no transitions through 0°C other than the initial freezeup in December and the thaw in April. Surface soil temperatures were moderated by the presence of a snow cover during most of the winter.

The second boundary condition, BC-Warmest, was created from BC-Warm by eliminating the period corresponding to 1 January through 17 March. This is based on a comparison of air-temperature extremes during the winter at the South Royalton site, at a coastal site in Washington state, and at a site in southern England. BC-Warmest, for which the surface soil is barely colder than 0°C for ~50 days, represents the mildest winter condition in terms of both the duration of below-freezing soil temperatures and the coldness of the soil.

The third boundary condition, BC-Cold, is derived from measured temperatures at a location at the South Royalton site where the snow cover was removed throughout the winter. It represents a more severe winter condition of generally lower surface temperatures than that represented by BC-Warm. By midwinter, the absence of a persistent snow cover results in deeper frost penetration and lower temperatures at depth than at the snow-covered BC-Warm site. It also results in more erratic changes in the temperature of the exposed soil, and in higher near-surface temperatures on winter days of high incident solar radiation. Similarly, under autumn and spring weather conditions, the absence of a vegetation cover to shelter the soil results in higher soil temperatures at this site than at the grass-covered BC-Warm site.

The fourth boundary condition, BC-Coldest, is created from BC-Cold by multiplying by three each of the negative temperatures composing BC-Cold; the positive temperatures are unchanged. This most severe winter condition corresponds to the temperature history of bare soil (no snow cover, no vegetation cover) during an unusually severe northern New England winter. More commonly, it corresponds to winter conditions in mid-continent northern states* or in interior Alaska where the snow cover is shallow (Sharratt 1993).

* Personal communication, D.G. Baker, Department of Soil Science, University of Minnesota, 1995.

Table 1. Properties of sandy soil for numerical simulations of heat flow.

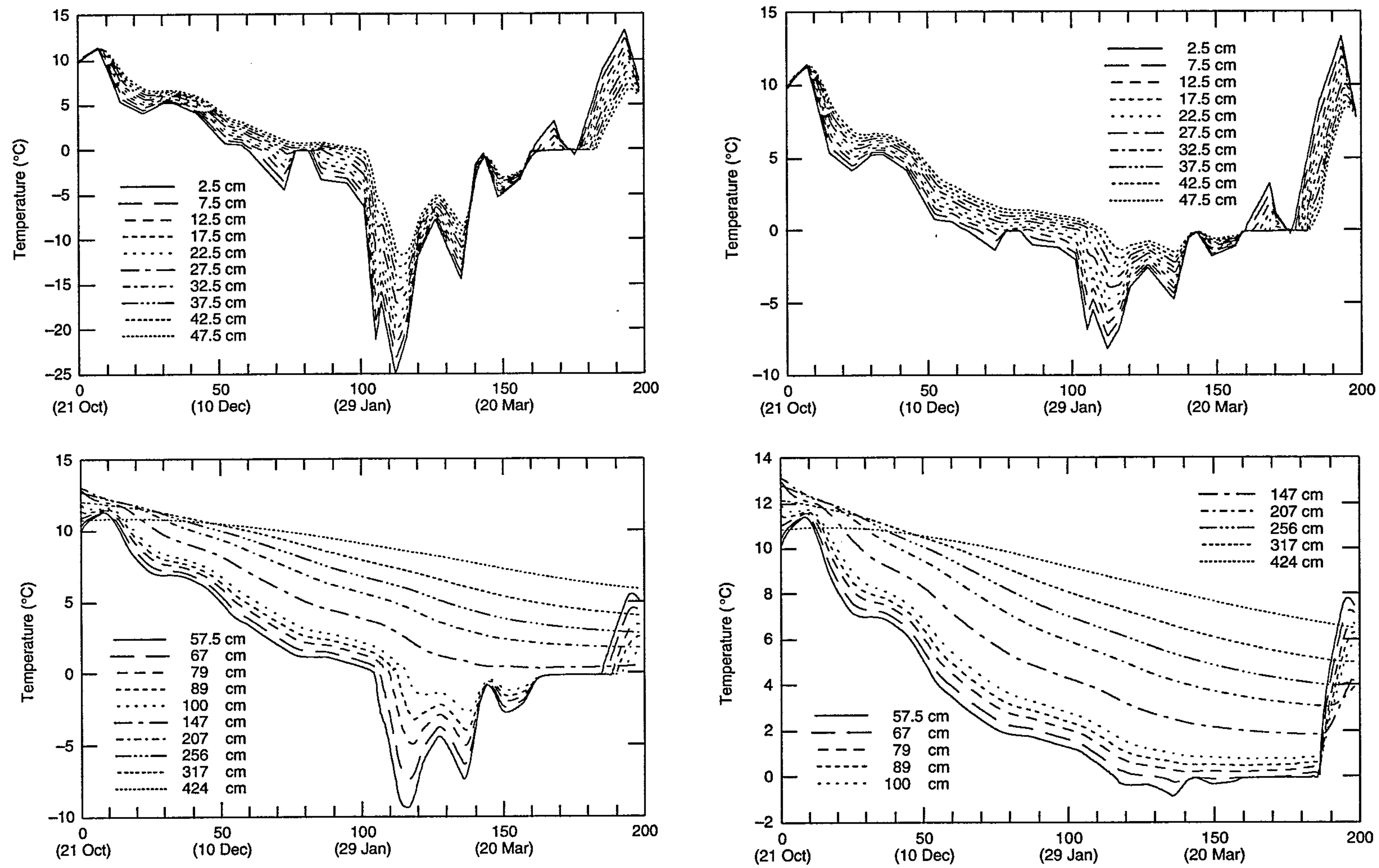
Sand designation	Moisture content (wt. %)	Dry density (g/cm³)	Thermal conductivity, unfrozen (10^{-3} cal/s/cm/°C)	Thermal conductivity, frozen (10^{-3} cal/s/cm/°C)	Volumetric mineral content (cm³/cm³)	Porosity	Latent heat (cal/cm³)	Volumetric moisture content (cm³ water/cm³ soil)	Volumetric heat capacity, unfrozen (cal/°C/cm³)	Volumetric heat capacity, frozen (cal/°C/cm³)
Sand 3	10	1.4	2.84	2.51	0.53	0.47	11.2	0.14	0.43	0.35
Sand 6	20	1.0	1.91	1.94	0.38	0.62	16.0	0.20	0.40	0.30
Sand 7	20	1.2	2.58	3.11	0.45	0.55	19.2	0.24	0.48	0.35
Sand 8	20	1.4	3.42	4.64	0.53	0.47	22.4	0.28	0.57	0.41
Sand 9	20	1.6	4.52	6.91	0.60	0.40	25.6	0.32	0.65	0.47
Sand 12	30	1.4	3.70	6.64	0.53	0.47	33.6	0.42	0.71	0.48

Material properties

For simulations the sandy soil is assigned the properties listed in Table 1. Volumetric heat capacity and thermal conductivity, for both the frozen and unfrozen state, and latent heat are specific input parameters of the computer program. Moisture content was chosen as 10, 20, and 30 wt. % on the basis of measurements of moisture content of the sandy loam at the South Royalton site at the beginning of winter (17–19 wt. %, nominally 20%), with the intention of considering cases of soil being dryer (10 wt. %) and wetter (30 wt. %) at the onset of freezing. Dry density of the soil was chosen to be 1.0, 1.2, 1.4, or 1.6 g/cm³. Soil porosity was calculated from dry density using a value of 2.65 g/cm³ for the mineral density of the soil. Latent heat of the soil was calculated for each combination of moisture content and dry density using the volumetric latent heat of water, 80 cal/cm³. Volumetric heat capacity of the soil for each combination of porosity and moisture content (converted to moisture content by volume) was calculated using a volumetric heat capacity of the mineral solids of 0.54 cal/cm³ °C, that of liquid water as 1 cal/cm³ °C, and that of ice as 0.46 cal/cm³ °C. The thermal conductivities of the soil are taken from plots of the average frozen and unfrozen thermal conductivity of sandy soils as a function of water content and dry density in Andersland and Anderson (1978, Fig. 3.6 and 3.7, respectively). The Andersland and Anderson figures are based on data for Fairbanks sand, Lowell sand, Chena River gravel, and Dakota sandy loam, and are valid for moisture contents of 1% or greater and clay-silt contents of less than approximately 20%.

Soil temperature profiles

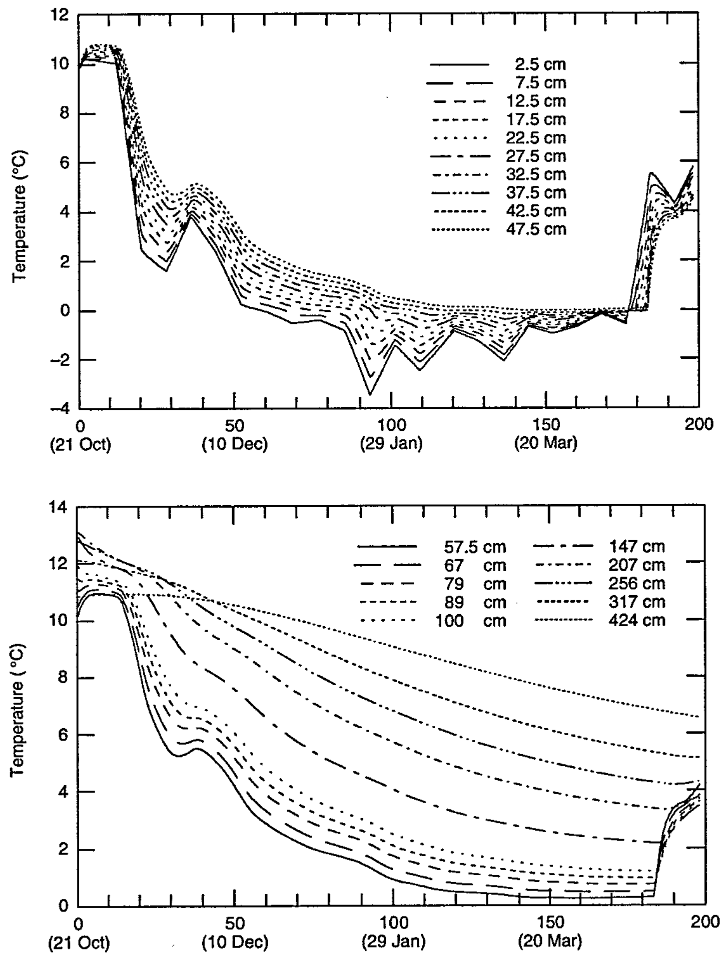
The simulations provided soil temperatures for depths of 2.5 cm to 9.6 m, but only temperatures for depths of ~4.25 m or less are presented here. Figure 5 shows soil temperature profiles in sandy soil for each of the winter conditions (BC-Coldest, -Cold, -Warm, -Warmest) with the same moisture content (20 wt. %) and porosity (0.47); temperature profiles for sandy soil of different moisture content and porosity are similar in shape. With increasing winter severity from BC-Warmest to BC-Coldest, the soil freezes to greater depth, the soil above the freezing front is colder, and below-freezing soil temperatures at a given depth persist longer. Taking a soil temperature of 5°C as the lower limit of significant nitrification and denitrification by microbes, it is clear that



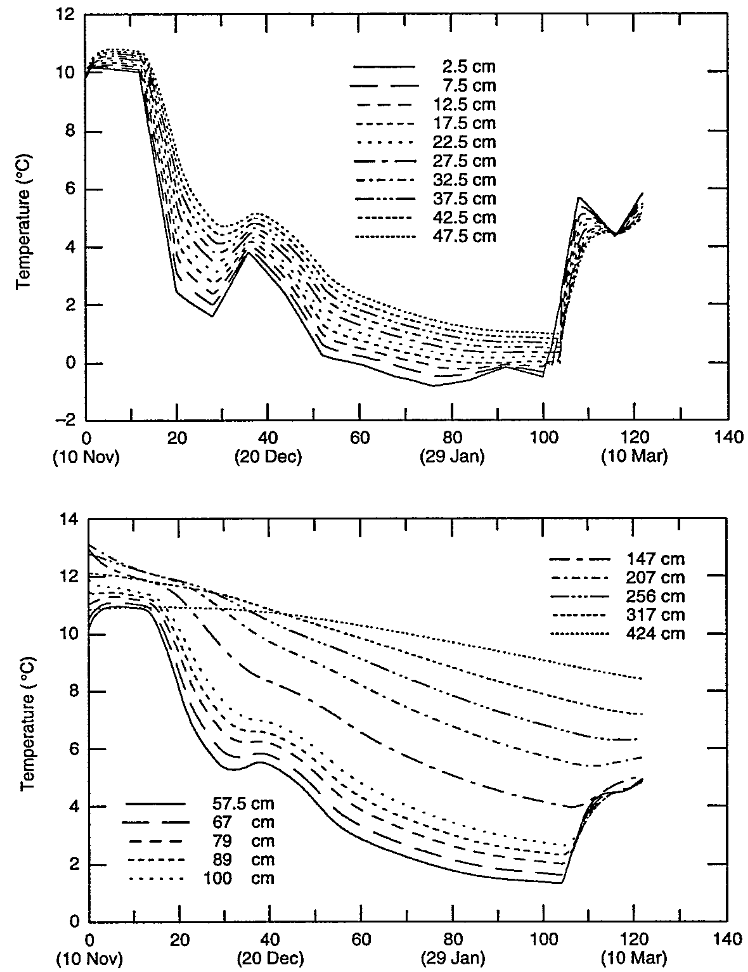
a. BC-Coldest.

b. BC-Cold.

Figure 5. Temperature profiles for sandy soil of 20 wt. % moisture content and 0.47 porosity, as determined with numerical simulations. The X-axis shows both the elapsed time with the winter-long simulations and selected corresponding dates.

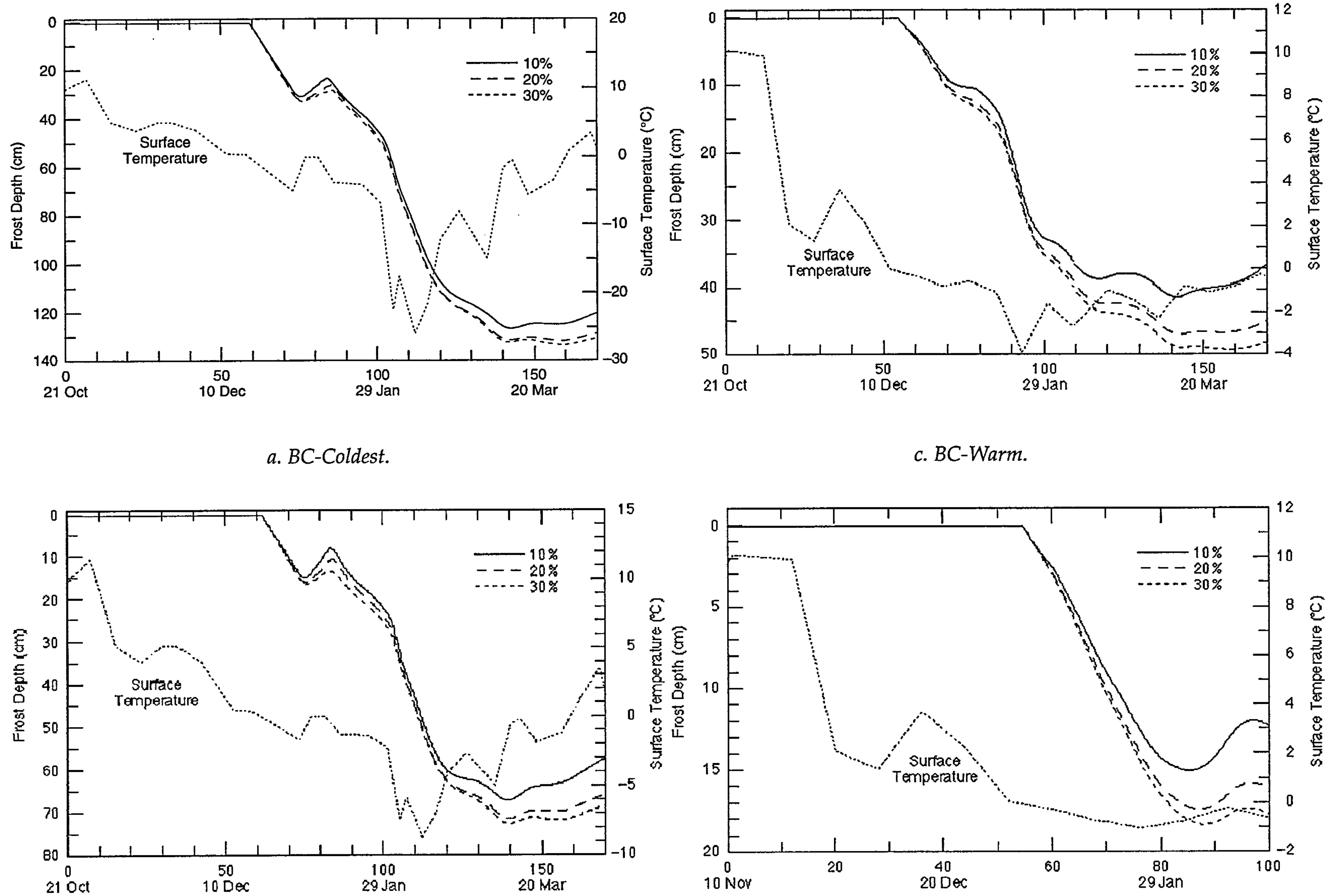


c. BC-Warm.



d. BC-Warmest.

Figure 5 (cont'd).



a. BC-Coldest.

b. BC-Cold.

c. BC-Warm.

d. BC-Warmest.

Figure 6. Frost depth in sandy soil with 0.47 porosity, as a function of moisture content, as determined with numerical simulations. The X-axis shows both the elapsed time with the winter-long simulations and selected corresponding dates.

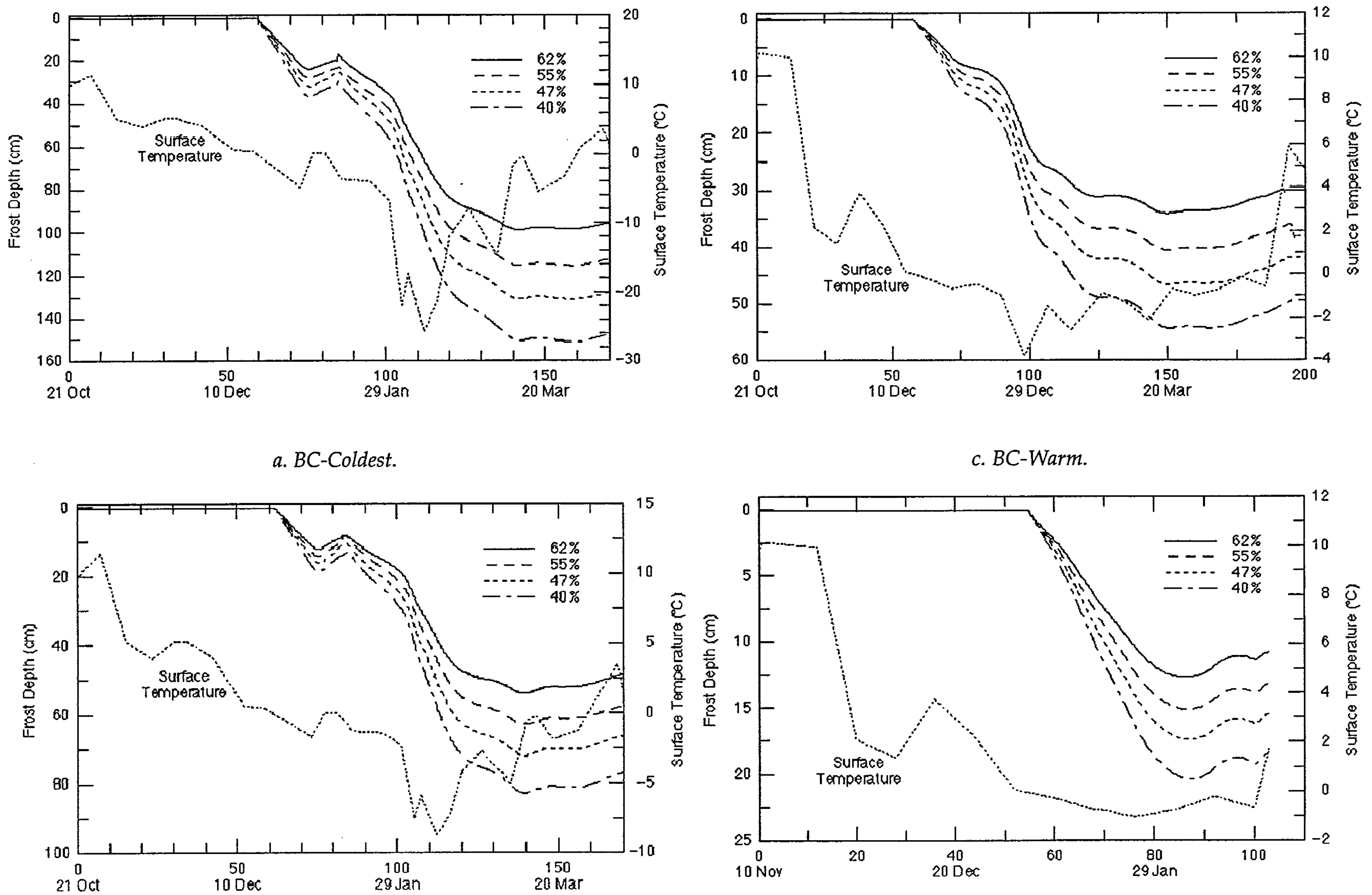
Table 2. Soil temperatures (°C) as a function of winter severity, date, moisture content, and depth, from simulations with sandy soil of 0.47 porosity.

Winter condition	*Day*	*Moisture content (wt. %)*	*Depth (cm)* 7.5	17.5	27.5	47.5	100.0	147.0
Coldest	50 (10 Dec)	10	1.70	2.42	3.09	4.27	6.61	8.03
		20	1.73	2.49	3.18	4.41	6.82	8.25
		30	1.78	2.59	3.33	4.62	7.12	8.58
	100 (29 Jan)	10	–5.22	–3.75	–2.33	0.11	2.15	3.73
		20	–5.30	–3.91	–2.55	0.04	2.23	3.91
		30	–5.34	–3.98	–2.65	–0.06	2.41	4.22
	150 (20 Mar)	10	–4.46	–4.06	–3.64	–2.79	–0.78	0.69
		20	–4.49	–4.14	–3.77	–3.01	–1.05	0.57
		30	–4.50	–4.16	–3.81	–3.08	–1.13	0.58
Cold	50 (10 Dec)	10	1.70	2.42	3.09	4.27	6.61	8.03
		20	1.73	2.49	3.18	4.41	6.82	8.25
		30	1.78	2.59	3.33	4.62	7.12	8.58
	100 (29 Jan)	10	–1.41	–0.47	0.18	0.91	2.68	4.10
		20	–1.46	–0.59	0.14	0.91	2.79	4.30
		30	–1.50	–0.68	0.10	0.93	2.99	4.62
	150 (20 Mar)	10	–1.41	–1.18	–0.93	–0.42	0.94	2.14
		20	–1.42	–1.21	–0.98	–0.52	0.86	2.18
		30	–1.43	–1.22	–1.00	–0.55	0.90	2.35
Warm	50 (10 Dec)	10	1.04	1.70	2.32	3.44	5.77	7.31
		20	1.06	1.76	2.41	3.57	5.99	7.58
		30	1.11	1.85	2.54	3.78	6.31	7.92
	100 (29 Jan)	10	–1.28	–0.78	–0.26	0.55	2.38	3.85
		20	–1.29	–0.82	–0.34	0.52	2.49	4.04
		30	–1.30	–0.84	–0.36	0.54	2.71	4.38
	150 (20 Mar)	10	–0.75	–0.51	–0.28	0.18	1.43	2.52
		20	–0.77	–0.57	–0.37	0.03	1.39	2.57
		30	–0.78	–0.59	–0.40	–0.02	1.47	2.77
Warmest	30 (10 Dec)	10	2.51	3.00	3.52	4.61	7.32	9.15
		20	2.53	3.05	3.60	4.74	7.56	9.41
		30	2.56	3.12	3.72	5.00	7.93	9.79
	80 (29 Jan)	10	–0.39	0.13	0.53	1.31	3.25	4.80
		20	–0.44	0.07	0.49	1.33	3.41	5.04
		30	–0.45	0.04	0.51	1.43	3.69	5.42
	130 (20 Mar)	10	NA	NA	NA	NA	NA	NA
		20	NA	NA	NA	NA	NA	NA
		30	NA	NA	NA	NA	NA	NA

even for the mildest winter condition, the soil is inhospitably cold to at least 1.5-m depth for some portion of the winter. The influence of the severity of the winter is evident in Table 2, which for sandy soil of porosity 0.47 compares soil temperatures at depths of 7.5, 17.5, 27.5, 47.5, 100, and 147 cm on day 50 (early winter), day 100 (midwinter), and day 150 (late winter) of the simulations, which correspond to 10 December, 29 January, and 20 March. Also apparent in the table are differences in soil temperatures as the result of the soil being drier (10 wt. %) or wetter (30 wt. %) at the onset of freezing. 5°C is an arbitrary, conservative value against which to assess how significantly the efficiency of land treatment of wastewater is changed by winter soil temperatures. Nitrification and denitrification processes proceed so slowly at temperatures below 5°C that they are no longer effective in treating wastewater on reasonable time scales, such as a 4- to 7-day interval between applications of wastewater.

The effect of soil wetness on frost penetration is shown in Figure 6 and summarized in Table 3. The greatest change in frost penetration in the sandy soil occurs when the moisture content increases from 10 wt. % to 20 wt. %; a further increase in wetness, to 30 wt. % moisture content, results in only a slight increase in frost depth.

The effect of soil porosity on frost penetration in the soil is evident in Figure 7, which shows the histories of frost depth in sandy soil of 20 wt. % moisture content. For each winter condition, frost depth increases with decreasing soil porosity due to the increased efficiency of heat transfer in the denser soil. Maximum frost depths are summarized in Table 3.



a. BC-Coldest.

c. BC-Warm.

b. BC-Cold.

d. BC-Warmest.

Figure 7. Frost depth as a function of soil porosity for sandy soil with 20 wt. % moisture content, as determined with numerical simulations. The X-axis shows both the elapsed time with the winter-long simulations and selected corresponding dates.

Table 3. Maximum frost depth (0°C isotherm) as a function of soil moisture content, soil porosity, and winter severity.

Moisture content (wt. %)	*Porosity*	*Winter condition*	*Max. frost depth (cm)*
10	0.47	Coldest	126.0
		Cold	67.1
		Warm	41.1
		Warmest	15.0
20	0.62	Coldest	98.8
		Cold	53.6
		Warm	34.1
		Warmest	12.6
20	0.55	Coldest	115.5
		Cold	62.6
		Warm	40.6
		Warmest	15.0
20	0.47	Coldest	131.2
		Cold	71.4
		Warm	46.6
		Warmest	17.3
20	0.40	Coldest	151.3
		Cold	82.3
		Warm	54.4
		Warmest	20.2
30	0.47	Coldest	132.9
		Cold	72.6
		Warm	48.9
		Warmest	18.2

For soil remediation applications, the consequences of varying soil porosity are more obvious in Figure 8. The minimum soil temperature attained at a given depth in the soil during the course of a particular winter (BC-Coldest, -Cold, -Warm, or -Warmest) is shown for the four soil porosities considered; soil moisture content is 20 wt. %. If it is known that a remediation process becomes ineffective at a particular temperature, e.g., ~5°C for nitrifying and denitrifying bacteria, then from Figure 8 one can determine the thickness of the soil layer which will become too cold for that remediation treatment to proceed during the type of winter under consideration. Use of Figure 8 in this way assumes that soil temperature is the only rate-limiting factor influencing remediation in winter, i.e., that the supply of oxygen and carbon is adequate for microbial activity.

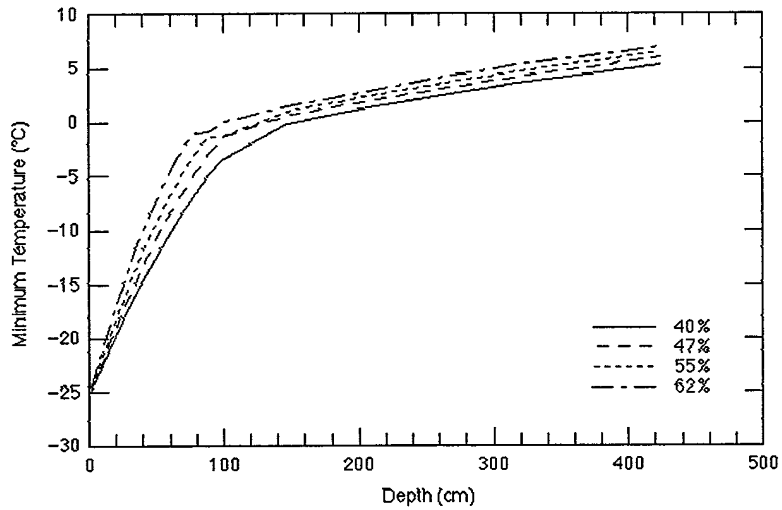
The actual interruption in remediation depends on the duration of the soil being so cold that it is inhospitable to, for example, nitrifying and denitrifying bacteria. Table 4 lists the number of days that soil at a given depth is colder than 5°C for a particular winter condition; the days on which this occurs are shown in Figure 9. As expected, the portion of the winter during which soil at these depths is colder than 5°C is least for the mildest winter (BC-Warmest). It is perhaps surprising that the two most severe winters (BC-Cold, BC-Cold-

Table 4. Number of days that soil at a given depth is colder than 5°C.

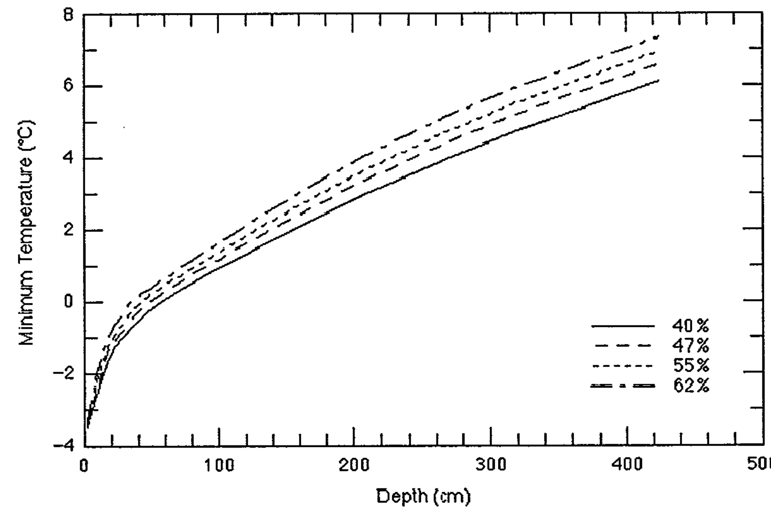
Winter condition	*Depth (cm)*	*Sand 3*	*Sand 6*	*Sand 7*	*Sand 8*	*Sand 9*	*Sand 12*
Warmest	2.5	95.25	95.25	95.25	95.25	95.25	95.25
	12.5	96.0	96.75	97.5	96.75	96.75	97.0
	27.5	99.0	98.25	98.75	99.0	99.5	98.75
	47.5	94.25	78.25	>87.25	88.0	92.25	>86.0
Warm	2.5	171.5	172.0	173.0	172.0	172.25	173.5
	12.5	177.0	177.0	177.25	177.25	177.25	178.0
	27.5	176.75	>177.75	>178.25	>178.25	>179.25	>178.25
	47.5	>93.0	>156.5	>175.75	>166.25	>170.5	>161.0
Cold	2.5	155.0	154.75	155.25	155.0	155.0	155.0
	12.5	146.75	144.75	147.75	146.25	147.25	145.75
	27.5	140.5	140.5	141.0	142.25	141.75	143.0
	47.5	138.5	138.25	139.0	140.25	142.0	142.25
Coldest	2.5	155.25	155.0	155.5	155.25	155.25	155.25
	12.5	147.25	145.5	145.75	146.5	147.5	145.7
	27.5	142.5	145.0	142.0	142.0	141.75	142.0
	47.5	145.0	>150.5	142.75	142.5	142.5	142.5

In those cases that the soil remained colder than 5°C at the end of the simulation, known minumum duration is listed with a > designation.

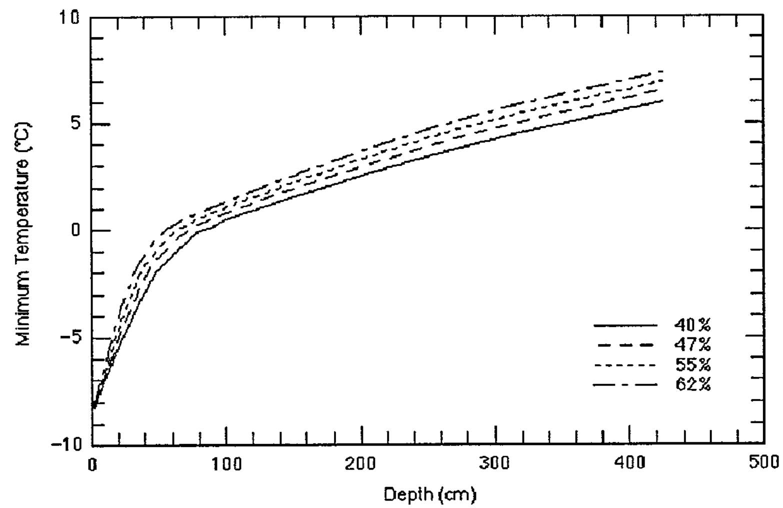
The sand designations correspond to Table 1 entries.



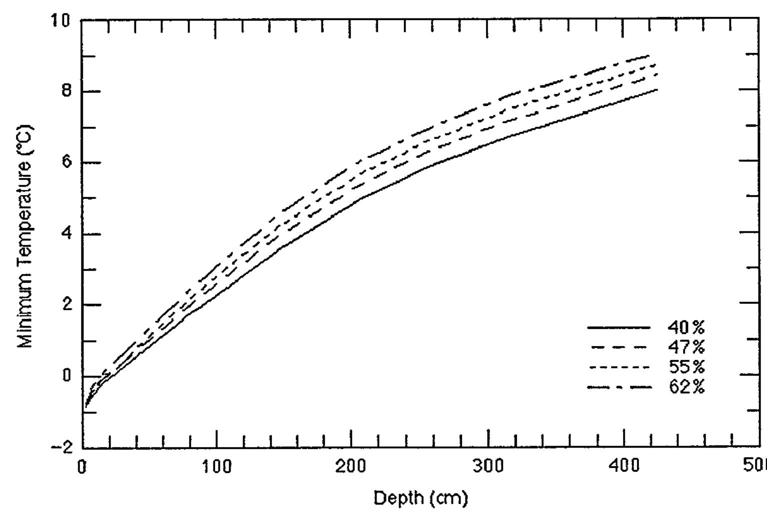
a. BC-Coldest.



c. BC-Warm.



b. BC-Cold.



d. BC-Warmest.

Figure 8. Minimum soil temperature as a function of depth and soil porosity, in sandy soil with 20 wt. % moisture content, as determined with numerical simulations.

est) result in shorter periods of below 5°C soil temperatures than does BC-Warm, with differences of 16–18 days for 2.5-cm-deep soil and 30–32 days for 12.5-cm-deep soil. The explanation for this lies in Figure 4. Early and late in the simulated winters, soil surface temperatures are warmer for BC-Cold and BC-Coldest than for BC-Warm. This results in a November window of soil temperatures suitable for remediation of wastewater, and earlier resumption of suitable soil temperatures in April.

The reason that the measured near-surface soil temperatures at the Vermont field site sometimes are warmer at the BC-Cold/BC-Coldest location than at the BC-Warm location is that the former has no grass cover, so the soil is more readily heated by absorption of solar radiation. This results in the near-surface soil being warm enough for microbial activity to occur during a larger portion of the year, suggesting that there is some advantage to not growing a vegetation cover on acreage used for land remediation of wastewater. A disincentive for leaving the land bare of ground cover is that the uptake of nitrogen species by plants is an important aspect of remediation. It may be practical to grow a ground cover during most of the year, but then to till the soil once the vegetation is dormant for the winter, particularly where a persistent snow cover is unlikely, thereby benefiting from both nitrogen uptake by growing plants and occasional warmer temperatures during winter in near-surface soil exposed to strong solar radiation.

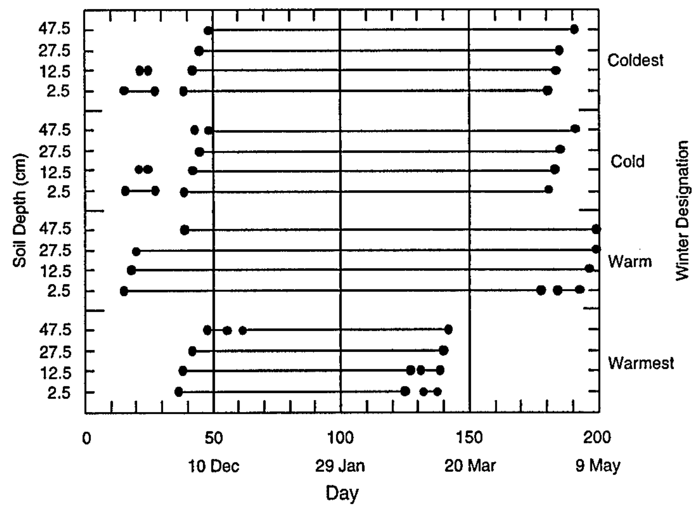


Figure 9. Periods when soil at a given depth is colder than 5°C are indicated with horizontal lines. Soil temperatures were predicted by numerical simulations for a sandy soil of 20 wt. % moisture content and 0.47 porosity under the four winter conditions (BC-Coldest, BC-Cold, BC-Warm, BC-Warmest).

DISCUSSION OF SOIL TEMPERATURE EFFECTS

Any temperature-dependent component of soil remediation treatments is subject to loss of effectiveness during the winter. The impact of the winter season on remediation treatments involving microorganisms depends on the depth and duration of inhospitable, yet above-freezing soil temperatures. In turn, depth and duration depend on soil moisture content and porosity, and on severity of the winter. Winter severity has the strongest influence on the potential for remediation of wastewater in winter by land treatment. The four representative winter conditions employed in the heat transfer simulations are intended to bound the variation in soil temperatures at a site arising from differences in winter severity from year to year. That is, mid-continental locations might experience winters ranging between BC-Cold and BC-Coldest, while remediation sites in mid-Atlantic states might more typically experience winter conditions ranging from BC-Warmest to BC-Warm.

A second consideration is the actual freezing of the soil, which if it occurs when the soil is moist, is likely to result in a nearly impermeable surface layer. During a BC-Warmest type of winter, only the top 10 to 20 cm of the soil column, depending on soil porosity, cools to less than 0°C. The soil remains frozen for ~45 days, and then thaws under the combined effects of surface warming and heat flow from the warmer soil at depth. During the most severe winter considered, BC-Coldest, maximum frost depth ranges from ~100 to 150 cm, depending on soil porosity. Maximum frost penetration occurs ~80 days after the onset of soil freezing; the entire soil column above the frost line remains frozen for at least 30 more days before the onset of thawing from the surface downward. For intermediate winter conditions, BC-Warm and BC-Cold, maximum frost depth is less than with BC-Coldest, but the layer of frozen soil that forms is also present for ~110 days. Thus, soil remediation treatments potentially are ineffective for one-eighth to one-third of the year, depending on the severity of winter conditions at a site, due to the possible formation of a surface layer impermeable to applied wastewater.

It is possible for nitrification and denitrification to continue in the warmer soil beneath a frozen surface layer (provided the supply of oxygen and carbon is adequate); however, because nitrifying and denitrifying bacteria are less numerous at depth (e.g., Ardakani et al. 1974), the rate of remediation of previously infiltrated wastewater will be slow.

Soil variables also can affect the efficacy of remediation techniques from year to year. If the soil is compacted, frost penetration will be deeper under the same winter conditions; if the soil is dryer at the onset of winter, then frost depth will be less. Assuming that the deeper the frost layer, the less effective the soil remediation treatment is, then compaction of the soil will slow remediation and drying of the soil will enhance remediation.

EXAMPLES OF WASTEN PREDICTIONS

In investigating the influence of soil temperature on land treatment of wastewater, specifically nitrogen species, only the rates of nitrification and denitrification are changed to reflect the slower rate of microbial activity at low temperatures. Plant uptake of water and nitrogen from the soil, as expressed by two terms, the nitrogen uptake rate (mg N/cm of root length per day) and the evapotranspiration rate (cm/day), are deliberately left unchanged, i.e., they proceed at "warm-soil" rates even during "cold-soil" and "cool-soil" simulations. Realistically, these terms also would vary seasonally, being larger during the growing season and smaller during winter when the plants reasonably might be expected to be dormant. In order to isolate the influence of soil temperature on wastewater remediation solely through its effect on nitrification and denitrification, however, variability in plant uptake of nitrogen is not considered in the WASTEN simulations conducted for this report. Selim and Iskandar (1980) present results of a sensitivity analysis for the influence of nitrogen uptake rate on the concentration distribution of nitrate in the soil profile and on the cumulative nitrogen uptake with time.

Two treatment scenarios are modeled. In the first, 5 cm of wastewater is applied over 4 hours; the concentration of applied ammonium in the wastewater is 32.36 mg/L, that of applied nitrate is 2.48 mg/L; the nitrogen uptake rate is 0.024 mg N per cm of root length per day; and the evapotranspiration rate is 0.3 cm/day. In the second scenario, 20 cm of wastewater is applied over 24 hours; the wastewater has zero ammonium and a nitrate concentration of 4 mg/L; there is no nitrogen uptake by plant roots; and the evapotranspiration rate is 0.3 cm/day. These scenarios are subsequently referred to as "5-cm wastewater" and "20-cm wastewater," respectively. In both cases the soil column has three layers (15, 30, and 105 cm thick) above the water table, which is at a depth of 150 cm. The water parameters, bulk densities, and saturation values of the soil layers are the same for both scenarios. Initial distributions of ammonium and nitrate are shown in Figure 10 (ammonium distribution is the same for both scenarios).

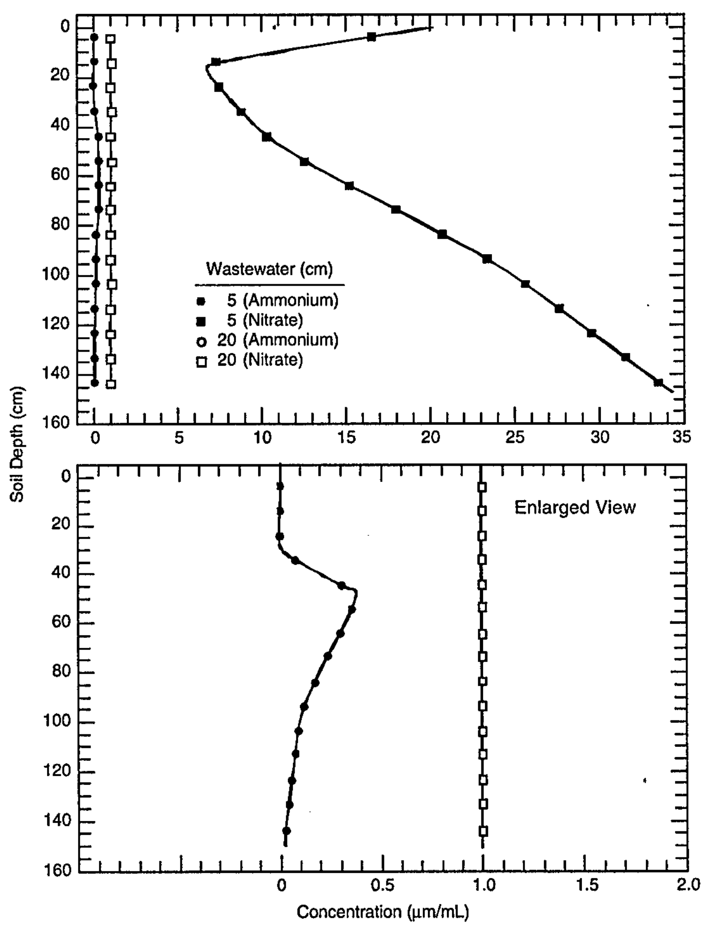


Figure 10. Initial distributions of ammonium and nitrate in soil for two simulations with WASTEN, 5-cm wastewater and 20-cm wastewater.

Table 5. Rate coefficients for nitrification and denitrification used in WASTEN simulations.

Case	*Soil layer*	*Layer thickness (cm)*	*Nitrification rate (hr^{-1})*	*Denitrification rate (hr^{-1})*
1: Warm soil	1	15	0.1	0.01
(standard values)	2	30	0.1	0.01
	3	105	0.1	0.01
2: Cold top layer	1	15	0.033	0.0025
	2	30	0.1	0.01
	3	105	0.1	0.01
3: Cold top 2 layers	1	15	0.033	0.0025
	2	30	0.033	0.0025
	3	105	0.1	0.01
4: Cool top layer	1	15	0.066	0.005
	2	30	0.1	0.01
	3	105	0.1	0.01
5: Cool top 2 layers	1	15	0.066	0.005
	2	30	0.066	0.005
	3	105	0.1	0.01

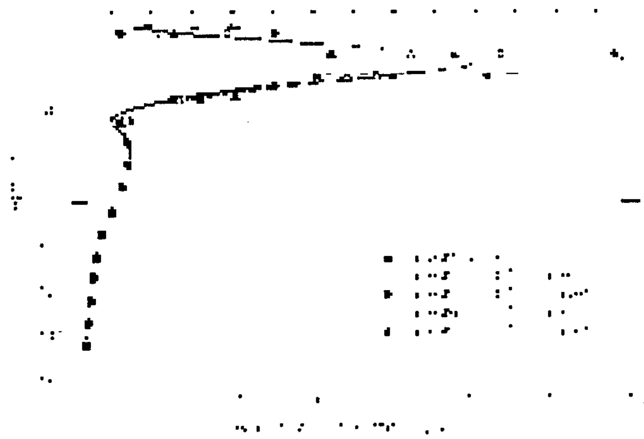
Five simulations were done for each wastewater application scenario. The only variables were the rate coefficients for nitrification and denitrification (Table 5); the ammonium exchangeable coefficient was left constant at 0.25 cm^3/gm. Case 1 uses the default values suggested for use with WASTEN; this is the warm-soil situation. Case 2 corresponds to a cold top layer (15 cm) of soil; the nitrification rate is reduced to one-third of the warm-soil value, and the denitrification rate is reduced to one-fourth of the warm-soil value. Case 3 corresponds to the top two soil layers (total of 45 cm) being cold; the same reduced rates of nitrification and denitrification are applied to both layers. Cases 4 and 5 correspond to less severe reductions in the nitrification and denitrification rates, affecting only the top layer or both soil layers, respectively. For these cool-soil situations, the nitrification rate is two-thirds that for the warm soil, and the denitrification rate is one-half that of the warm soil. Although the rates chosen for the cold and cool soil are arbitrary, the amount of the reductions relative to the rates in warm soil was guided by the examples of the temperature dependence of nitrification and denitrification that were presented in the Factors Influencing Nitrification and Denitrification section of this report.

The results of the WASTEN simulations are presented in Figure 11 for the 5-cm wastewater scenario and in Figure 12 for the 20-cm wastewater scenario. The smallest peak concentrations of ammonium and nitrate are found in the warm soil as expected, because nitrification and denitrification would have proceeded the most rapidly in this soil. Concentrations are greater in cold soil than in cool soil for the same layer thickness of reduced temperature soil. Concentrations are greater in soil having two layers of reduced temperature soil than in soil with one layer of cold or cool soil. In the former cases, nitrification and denitrification proceed less rapidly in the top 45 cm of soil, whereas only the top 15 cm of soil is affected by lower temperatures in the latter cases. (The exception to this is the concentration of ammonium in soil for the 20-cm wastewater scenario; because the wastewater contains no ammonium, there is no differentiation in ammonium concentration at the end of three days among the five soil cases.)

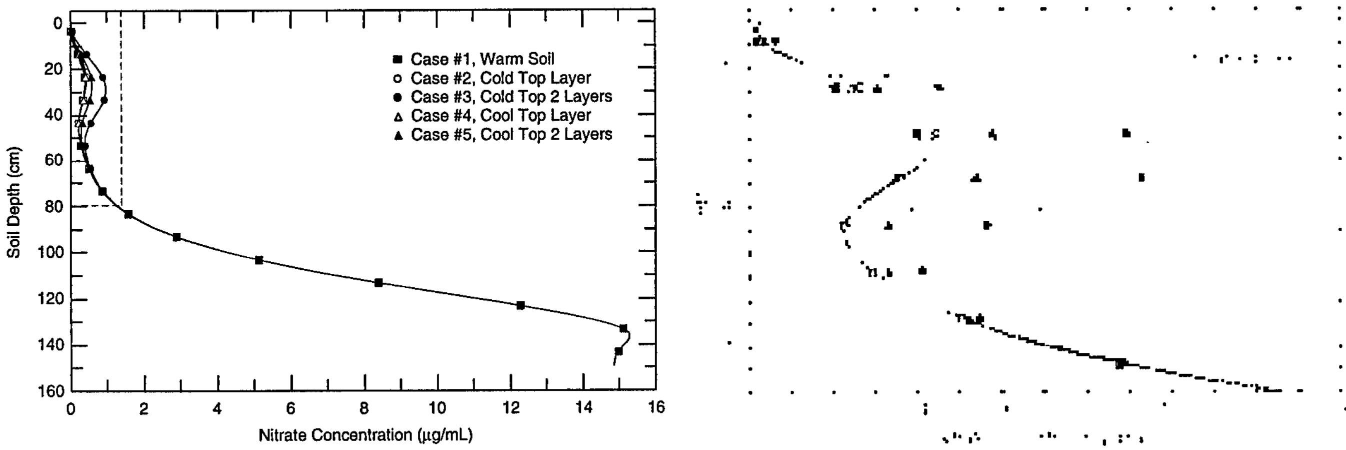
The presence of the thick (45 cm) cold layer of soil results in increases of 40–100% in peak concentrations of ammonium and nitrate at the end of the specified period (three or four days). Whether these larger amounts are significant depends on the objectives of the wastewater treatment, i.e., the acceptable levels of ammonium and nitrate in the soil following wastewater application. Clearly, however, the inclusion of temperature-dependent reductions in the rates of nitrification and denitrification results in appreciable differences in the amount of ammonium and nitrate in the soil.

SUMMARY AND CONCLUSIONS

The impact of the winter environment on land treatment of wastewater has been investigated in terms of predicted winter-long soil temperature histories and depths of frost penetration that were obtained from numerical modeling of heat transfer and phase change in sandy soil. Four representative winter conditions were used as surface boundary conditions for the simulations. Soil



a. *Ammonium.*



b. *Nitrate.*

Figure 11. WASTEN predictions for ammonium and nitrate in soil four days after a surface application of wastewater to a depth of 5 cm (5-cm wastewater scenario).

a. *Ammonium.* b. *Nitrate.*

Figure 12. WASTEN predictions for ammonium and nitrate in soil three days after a surface application of wastewater to a depth of 20 cm (20-cm wastewater scenario).

moisture content (10, 20, 30 wt. %) and porosity (0.40, 0.47, 0.55, 0.62) were varied to study the dependence of the soil temperature histories on these factors. The results are summarized in plots of minimum soil temperature as a function of depth. From these plots the depth to which any temperature-dependent remediation process becomes ineffective during winter can be estimated.

Although the results of the heat transfer simulations are applicable to any type of land-based remediation process, they were applied here to the situation of nitrification of ammonium and denitrification of nitrate by bacteria. Because nitrification and denitrification effectively cease at ~5°C, particular attention was paid to how many days during each type of winter the soil (at selected depths) was colder than 5°C. This identifies limitations on the usefulness of land treatment of wastewater in seasonally cold regions.

The model WASTEN was run to simulate two wastewater application scenarios. As examples of the reduction in effectiveness of land treatment of nitrogen compounds as soil temperatures approach 5°C, the standard rate of nitrification (0.1 hr^{-1}) used with WASTEN was reduced to one-third its value to represent cold soil and to two-thirds its value to represent cool soil. Similarly, the standard rate of denitrification (0.01 hr^{-1}) used with WASTEN was reduced to one-quarter and one-half its value, respectively. The predicted concentrations of ammonium and nitrate near the soil surface are larger the colder the soil is, and for a given soil coldness, larger the thickness of the cold soil layer. These results are intuitively consistent with the reduced effectiveness of the nitrification and denitrification processes.

A complete investigation of the impact of winter conditions on remediation treatments would include not only soil temperatures, but also seasonal differences in processes such as evapotranspiration and plant uptake of nitrate. For situations in which microorganisms are primarily responsible for remediation, however, the results in this report are indicative of the reduction, even cessation, of wastewater treatment that may occur in winter. Winter soil temperatures, and their variation with depth, severity of the winter, soil porosity, and soil moisture content, should be considered when deciding whether land treatment of wastewater is viable at a seasonally cold site.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1998	

4. TITLE AND SUBTITLE
Remediation of Wastewater by Land Treatment:
Consideration of Soil Temperatures in Winter

5. FUNDING NUMBERS

6. AUTHORS
Lindamae Peck

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER
CRREL Report 98-8

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of the Chief of Engineers
Washington, D.C. 02314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES For conversion of SI units to non-SI units of measurement consult *Standard Practice for Use of the International System of Units (SI)*, ASTM Standard E380-93, published by the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, Pa. 19428-2959.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.
Available from NTIS, Springfield, Virginia 22161.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The impact of the winter environment on land treatment of wastewater has been investigated in terms of predicted winter-long soil temperature histories and depths of frost penetration that were obtained from numerical modeling of heat transfer and phase change in sandy soil. Severity of the winter, soil porosity, and soil moisture content are varied to determine the depth-dependent changes in soil temperature that result. The impact of wintertime soil temperatures on nitrification and denitrification is presented in terms of thickness and persistence of a soil layer cold enough to severely inhibit microbial activity. The model WASTEN is used to predict concentrations of ammonium and nitrate in soil at the end of a remediation cycle. Rates of nitrification and denitrification are varied to be consistent with decreasing microbial activity as soil cools. Depending on soil temperature and thickness of the cold soil layer, peak concentrations of ammonium and nitrate remaining in the soil can be as much as 40–100% greater than under warm soil conditions.

14. SUBJECT TERMS

Bioremediation	Nitrification	Wastewater
Frozen ground	Simulation	Winter
Denitrification	Soil temperature	

15. NUMBER OF PAGES
21

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102